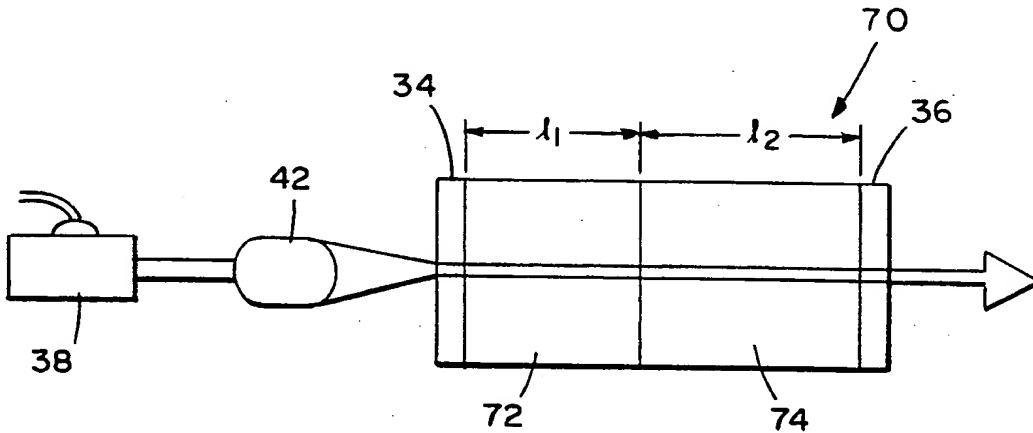


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(54) Title: MICROCHIP LASER



## (57) Abstract

A gain medium (32) is disposed between two mirrors (34, 36) to form a resonant cavity. The cavity length (l) is selected so that the gain bandwidth of the gain medium is less than or substantially equal to the frequency separation of the cavity modes and such that a cavity mode frequency falls within the gain bandwidth. A nonlinear optical material (50) is disposed either inside or outside the cavity to generate new laser wavelengths. The nonlinear optical material (50) may be contained in a cavity which is resonant at the microchip laser frequency. Alternatively, the microchip laser (30) may be tuned, for example thermally or by the application of a longitudinal or transverse stress, to the frequency of the resonant cavity. The laser is optically pumped by any appropriate source such as a semiconductor injection laser (38) or laser array. Suitable gain media include Nd:YAG, Nd:GSGG and Nd pentaphosphate, and suitable non-linear optical material include MgO:LiNbO<sub>3</sub> and KTP.

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### MICROCHIP LASER

#### Background of the Invention

This application is a continuation-in-part of U.S. Serial No. 151,396 filed February 2, 1988.

5 This invention relates to single frequency microchip lasers.

In this specification, numbers in brackets refer to the references listed at the end of the specification, the teachings of which are incorporated herein by reference.

10 The realization of practical single-frequency, diode-pumped, solid-state lasers has been the goal of several researchers over the past 20 years [1]. One approach has been the solid-state unidirectional, nonplanar, ring oscillator [2]. While this approach provides the desired laser  
15 characteristics, it suffers from a complicated fabrication process and optical alignment is critical. A simpler approach is the miniature, linear, solid-state cavity [3-5]. Although there has been some work on multimode miniature flat-flat cavities [6], the most common design for  
20 single-mode miniature cavities uses one curved mirror to stabilize the resonator [3-5]. In allowed U.S. Patent Application Serial No. 151,396, filed February 2, 1988, there is disclosed a solid-state, optically pumped microchip laser in which the cavity length is selected so that the  
25 gain bandwidth of the gain medium is less than the frequency separation of the cavity modes. This relationship guarantees that only a single longitudinal mode will oscillate when the frequency of this mode falls within the laser gain region.

30 Summary of the Invention

The solid-state optically pumped microchip laser according to one aspect of the invention includes a

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solid-state gain medium disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium is substantially equal to the frequency separation of the cavity modes. In another 5 aspect, a solid-state gain medium is disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium is less than or substantially equal to the frequency separation of the cavity modes. A nonlinear optical material is disposed to 10 receive light from the gain medium, the nonlinear optical material selected to generate second or higher harmonics of the light from the gain medium.

In yet another aspect of the invention, the microchip laser includes a solid-state gain medium/nonlinear 15 optical material combination disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium is less than or substantially equal to the frequency separation of the cavity modes. The nonlinear optical material is selected to generate second or 20 higher harmonics of the light from the gain medium.

By selecting the cavity length so that the gain bandwidth is substantially equal to the frequency separation of the cavity modest one is guaranteed that only one cavity frequency falls within the laser gain region and only one 25 laser frequency will oscillate. The inclusion of nonlinear optical material provides light in the visible or ultraviolet regions useful for read and write optical disks and for projection television applications, among others. Both the laser gain element and the nonlinear crystal are 30 dielectrically coated flat wafers. These wafers are bonded together with transparent optical cement and diced into many small sections which greatly reduces the cost and complexity

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of such lasers as compared with devices using discreet optical components that are fabricated and assembled separately.

The single frequency microchip lasers according to 5 the invention employ a miniature, monolithic, flat-flat, solid-state cavity whose mode spacing is greater than the medium gain bandwidth. These lasers rely on gain-guiding or nonlinear optical effects to define the transverse dimensions of the lasing mode. As a result of the 10 monolithic, flat-flat construction, the fabrication process for the microchip laser lends itself to mass production. The cost per laser is extremely low because of the small amount of material used for each laser and the simple fabrication. The resulting microchip lasers are 15 longitudinally pumped with the close-coupled, unfocused output of a diode laser.

Brief Description of the Drawing

Figs. 1.1 and 1.2, are graphs of laser gain and 20 oscillation modes versus frequency;

Figs. 2.1 and 2.2 are cross-sectional views of a microchip laser of the invention;

Fig. 3 is a graph of output intensity versus wavelength;

25 Fig. 4 is a graph of output power versus pump power for lasers of the invention;

Figs. 5.1 and 5.2 are graphs illustrating measured spectral response of the lasers of the invention;

Fig. 6 is a cross-sectional view of an embodiment 30 of the invention including a nonlinear optical element;

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Fig. 7 is a cross-sectional view of an embodiment of the invention with a nonlinear optical element incorporated within the laser resonant cavity;

Fig. 8.1 depicts an array of microchip lasers on a 5 wafer in association with a wafer of diode pump lasers; while Fig. 8.2 depicts the array of Fig. 8.1 in association with a wafer of nonlinear optical material with Fabry-Perot resonators; and

Fig. 9.1 depicts an embodiment of the microlaser 10 of Fig. 6 with an apparatus for stress tuning and Fig. 9b depicts an embodiment of the microlaser of Fig. 6 with an apparatus for thermal tuning.

#### Description of the Preferred Embodiment

15 The theory on which the present invention is based will now be discussed in conjunction with Fig. 1. In Fig. 1.1, a curve 10 is a plot of gain versus frequency for any solid-state laser gain medium such as Nd:YAG or Nd pentaphosphate. The gain bandwidth  $V_g$  of the curve 10 is 20 defined as the separation between arrows 12 and 14 wherein the gain exceeds the loss. Also shown in Fig. 1.1 are intracavity modes 16 and 18. The separation  $V_c$  between adjacent cavity modes is given by the equation  $V_c = c/2n\ell$  where c is the speed of light, n is the refractive index of 25 a gain medium and  $\ell$  is the length of a resonant cavity. As shown in Fig. 1.1, a cavity length  $\ell$  has been selected so that  $\ell$  is less than  $c/2nV_g$  resulting in the intracavity modes 16 and 18 being spaced greater than the gain bandwidth of the curve 10 and the absolute frequency of the cavity 30 mode  $V_a = mc/2n\ell$  where m is an integer such that the frequency falls outside the gain bandwidth. In the case illustrated the intracavity modes 16 and 18 straddle the

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gain curve 10 so that there will be no lasing of the gain medium since there is no overlap of the gain curve 10 with either of the modes 16 or 18. To insure that the gain medium will lase, it is necessary that there be at least 5 some overlap of the gain curve 10 with one of the intracavity modes such as the mode 18 as shown in Fig. 1b. Assuring such overlap is accomplished by an appropriate choice of gain material and cavity length.

With reference now to Fig. 2.1, a microchip laser 10 30 includes a solid-state gain medium 32 disposed between a pair of mirrors 34 and 36. The mirrors 34 and 36 are coated with multiple layers (20-30 layers) of dielectric material. The gain medium 32 is pumped optically by a laser 38 whose output light 40 is focused by a lens 42 onto the mirror 34. 15 The mirror 34 transmits light from the pump laser 38 but reflects light generated within the gain medium 32. The length  $\ell$  of the gain medium 32 is selected so that  $\frac{1}{2c/2n} \gamma_g$  where  $\gamma_g$  is the bandwidth of the gain medium. In this case, as pointed out above, a single mode only will oscillate 20 within the gain medium 32 when  $\gamma_a$  falls within the gain bandwidth so that the output light 44 from the laser 30 is single frequency. The mirrors 34 and 36 may be separate elements bonded directly to the gain medium 32 or they may be multilayer coatings deposited directly on the opposing 25 flat surfaces of the gain medium 32. In Fig. 2.2, the laser 38 is placed close to or bonded directly to the mirror 34 so that most of the light from the pump laser is absorbed in the fundamental mode region of the microchip laser.

To demonstrate the feasibility of diode-pumped 30 microchip lasers, several different microchip lasers were constructed and operated CW at room temperature. These included: Nd:YAG ( $\text{Nd}_x \text{Y}_{3-x} \text{Al}_5 \text{O}_{12}$ ) at  $1.06 \mu\text{m}$  using a 730-

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$\mu$ m-long cavity; Nd:YAG at 1.3  $\mu$ m using a 730- m-long cavity; Nd pentaphosphate ( $\text{NdP}_5\text{O}_{14}$ ) at 1.06 m using a 100- $\mu$ m-long cavity; and Nd:GSGG ( $\text{Nd}_x\text{Gd}_{3-x}\text{Sc}_2\text{Ga}_3\text{O}_{12}$ ) at 1.06  $\mu$ m using a 625- $\mu$ m long cavity. In each case, single-longitudinal-mode, single-spatial-mode operation was achieved with pump powers many times above threshold.

The performance of the 1.06  $\mu$ m Nd:YAG microchip lasers will now be discussed. These lasers were constructed from a slab of YAG with 1.1 wt. percent Nd doping. The slab was cut and polished to a thickness of 730  $\mu$ m. Dielectric cavity mirrors were deposited directly onto the YAG. On other microchip lasers the mirrors were cut from 100-m-thick wafer mirrors and then bonded to the Nd:YAG. The performance of the separate-mirror devices was very similar to the performance of the dielectrically coated Nd:YAG cavities. The output mirror 36 had a reflectivity of 99.7% at 1.06  $\mu$ m and was designed to reflect the pump laser. The opposite mirror 34 had a reflectivity of 99.9% at 1.06  $\mu$ m and transmitted the pump. The Nd:YAG was cut into pieces 1 mm square (or less) and bonded to a sapphire heat sink (not shown). Damage to the dielectric coatings from cutting the wafers was confined to a distance of less than 30  $\mu$ m from the edge of the chips.

A Ti:Al<sub>2</sub>O<sub>3</sub> laser was used as a pump source to characterize the microchip lasers prior to diode pumping. It was tuned to the Nd:YAG absorption peak at 0.809  $\mu$ m and focused onto the microchip laser, with an experimentally determined spot size of about 50  $\mu$ m in the Nd:YAG crystal. Measurements showed that 18% of the incident pump power was reflected by the laser package and 27% was transmitted. The efficiency of the microchip lasers can be improved with better dielectric coatings.

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When the Nd:YAG microchip laser was properly aligned with the pump, single-longitudinal-mode, single-spatial-mode operation was observed. The output beam 22 was circularly symmetric with a divergence of about 20 5 mrad, determined by the spot size of the pump. Spectrometer traces (Fig. 3) showed only single-longitudinal-mode operation for absorbed pump powers up to 40mW. The lasing frequency tuned slightly as the pump spot on the microchip cavity was moved to positions with a slightly different 10 cavity length. The devices constructed with wafer mirrors were continuously tunable over the entire gain spectrum by mechanical movement of the mirrors. In contrast to results reported in [7], the output polarization of the microchip laser was in the same direction as the polarization of the 15 pump to better than 1 part in 100.

A computer-controlled variable attenuator was introduced into the path of the pump beam to obtain the input-output power characteristics of the microchip laser. The lasing threshold was measured to be below 1 mW, and the 20 slope quantum efficiency (determined from the output of the laser from the 99.7% reflecting mirror only) was slightly greater than 30%. The input-output curve is shown in Fig. 4. At higher pump powers thermal effects led to unrepeatable results. The highest single-mode CW output 25 power achieved with the microchip laser was 22 mw.

The linewidth of the Nd:YAG microchip lasers was measured by heterodyning two free-running devices together. Thermal tuning was used in order to get the lasers to operate at nearly the same frequency. The outputs of the 30 lasers were stable enough to obtain heterodyne measurements with a resolution of 10 kHz. At this resolutions the measured spectral response was instrument limited. (See

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Fig. 5) This gives a linewidth for the microchip lasers of less than 5 kHz, assuming equal contributions to the linewidth from each laser. The theoretical phase fluctuation linewidth is estimated to be only a few hertz.

5 Relaxation oscillations account for the observed sidebands 700 kHz away from the main peak. The intensity of the sidebands varied with time but was always greater than 30 dB below the main peak.

The microchip Nd:YAG lasers have been pumped with  
10 the unfocused output of a 20-mW GaAlAs diode laser. The Nd:YAG cavity was placed about 20  $\mu$ m from the output facet of the diode laser and longitudinally pumped. The resulting pump spot size in the Nd:YAG was about 50  $\mu$ m in diameter. The output of the microchip laser showed  
15 single-longitudinal-mode, fundamental (i.e. lowest order) single-spatial-mode operation at all available powers. The divergence of the laser was diffraction limited at about 20 mrad.

Important embodiments of the present invention are  
20 shown in Fig. 6. In Fig. 6.1, a dielectrically coated flat wafer 50 of a nonlinear optical material is located to receive light from the microchip laser 30. The wafer 50 includes dielectric coatings 52 and 54. The nonlinear optical material of the wafer 50 has the property that, when  
25 exposed to monochromatic light, it generates a beam of light including harmonics of the incident beam. Suitable nonlinear optical materials are, for example, MgO:LiNbO<sub>3</sub> and KTP (potassium titanyl phosphate). As in the embodiments of Fig. 2, the cavity length  $\ell$  of the gain medium 32 satisfies  
30 the relationship  $\ell \leq c/2nV_g$ . Light from the microchip laser 30 passes into the nonlinear optical element 50 which shifts the frequency to one of the harmonics of the incident beam.

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A particularly useful harmonic is the second harmonic. The optical coatings 52 and 54 are chosen such that they form a Fabry-Perot cavity at the pump wavelength. Typical reflectivities of such coatings at the pump wavelength are 5 98%. Mirror 52 is also highly reflective at the harmonic wavelength while mirror 54 is highly transmissive at the harmonic wavelength. In addition to techniques whereby the cavity frequency of the harmonic crystal is tuned to the laser frequency, the single-frequency microchip laser may be 10 tuned to be resonant with any of the harmonic crystal cavity modes and may be locked to that frequency in any number of ways including monitoring of the intensity of the harmonic output power. The microchip laser may be continuously tuned by a number of techniques that are well known including the 15 application of a longitudinal or transverse stress to the crystal or by modifying the refractive index of the crystal thermally. Fig. 9.1 shows a microlaser 30 associated with a nonlinear optical material 50 located within a Fabry-Perot cavity made up of mirrors 52 and 54. The gain medium 32 of 20 the laser 30 is positioned between a fixed stop 912 and a movable stop 910. Pressure is applied (shown here as being applied by an adjustable screw 914) to the gain medium 32 through the movable stop 910. By adjusting the pressure on the gain medium 32, the frequency of the laser light can be 25 matched to the resonant frequency of the Fabry-Perot cavity. In Fig. 9.1, a transverse stress is being applied to the medium. It is possible to stress tune the laser by the application of a longitudinal stress along the direction of the laser light.

30 Fig. 9.2 shows a microlaser 30 associated with a nonlinear optical material 50 as in Fig. 9.1. However, in this embodiment the gain material 32 is positioned within a

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temperature regulating jacket 918 which can be heated or cooled by the temperature regulating elements 916. By adjusting the temperature of the gain medium 32 the frequency of the laser light can be thermally tuned to match 5 the resonant frequency of the Fabry-Perot cavity. Because the laser frequency can be changed by thermal tuning, it should also be noted that in order to stress tune a microlaser and have it remain tuned, it may be necessary to regulate the temperature of the gain medium.

10 The ability to continuously tune the microchip laser over its gain bandwidth without a mode jump is a significant advantage in being able to precisely tune and lock to any of the Fabry-Perot cavity modes of the harmonic crystal.

15 The harmonic crystal with its resonant cavity may be separate from the microchip laser or it may be bonded directly to the output end of the microchip laser using an optically transparent cement. The use of flat-flat cavities on the harmonic crystal simplify the fabrication process by 20 using similar wafer processing technology as that for the microchip laser. However, any of the well known techniques for a resonant harmonic cavity may also be used in conjunction with the microchip laser such as the unidirectional ring resonator or spherical mirror cavity. 25 Further, the nonlinear material may be incorporated within the laser cavity itself.

Fig. 6.2 shows a configuration similar to Fig. 6.1 but with the diode placed close to or bonded to the laser medium. Fig. 7 is an embodiment of the invention in which 30 nonlinear optical material forms a part of the laser cavity structure. A microchip laser 70 includes a flat wafer 72 of an active gain medium. A nonlinear optical element 74 is

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bonded to the gain medium 72. Dielectric mirrors 34 and 36 complete the microchip laser 70. The length  $\ell$  between the mirrors 34 and 36 satisfies the relationships

5

$$V_g \leq c/2(n_1 \ell_1 + n_2 \ell_2)$$

$$\ell = \ell_1 + \ell_2$$

Where  $\ell_1$ ,  $n_1$  are the length and index of refraction respectively of the gain medium and  $\ell_2$ ,  $n_2$  are the length and index of refraction of the non-linear material.

It will be appreciated by those skilled in the art that by selection of the appropriate nonlinear optical materials the output from the harmonically converted microchip laser can be in the visible or ultraviolet region 15 and be useful for read and write optical disks or projection television applications. It will also be appreciated that using the same fabrication techniques, an electro-optic or acousto-optic modulator can be incorporated into the composite structure with the modulator electrodes being 20 photolithographically incorporated onto the wafers before being diced up. Such fabrication techniques would greatly reduce the cost and complexity of such devices over those using discrete optical components that are fabricated and assembled separately.

25

In addition to harmonic generation by means of a suitable nonlinear material, nonlinear frequency conversion may be carried out in suitable nonlinear optical materials using optical parametric oscillation or amplification as well as frequency sum or difference mixing using the single 30 frequency microchip laser. Similar cavity fabrication as that described above may be used to create a microchip laser whose single frequency light is frequency converted by

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parametric conversion into light of two lower frequencies. In this parametric conversion microchip laser, the resonators differ from those previously described only in that the nonlinear optical material is a parametric 5 conversion material such as  $\text{LiNbO}_3$  or  $\text{KNbO}_3$  and the cavity coatings are chosen according to the well known art form for such devices.

Fabrication of the foregoing embodiments will now be discussed. A boule of laser material is grown by 10 conventional methods. The boule is sliced to the appropriate thickness depending on whether or not a nonlinear optical element is to be incorporated into the resonant cavity. The resulting wafer is lapped to the desired length, parallel and flat to better than one 15 wavelength using conventional lapping techniques. The wafer must be flat over the area being irradiated by the diode pump laser.

At this point, the gain medium is coated with multiple layers of dielectric material on opposite faces. 20 Alternatively, separate mirrors are bonded to the gain medium. The slice or wafer is then diced into individual microchip lasers which can be mounted to the pump optics.

The nonlinear optical elements used for frequency shifting are lapped flat and parallel and incorporated 25 either within or outside of the laser cavity as shown in Figs. 6 and 7. In the case in which the nonlinear optical material is outside the resonant cavity, both surfaces of the nonlinear material are coated with dielectric layers which are highly reflective to the frequency of light 30 generated by the microchip laser. In addition, the surface of the nonlinear optical material nearest to the microchip laser is coated with dielectric layers which are highly

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reflective of the wavelength of light generated by the nonlinear optical material. Although for ease of manufacture, the nonlinear element may be lapped with both surfaces flats it is also possible, in the case of the 5 optical material being outside the laser cavity, to have the surface away from the microchip laser be a nonflat surface.

Any non-parallel resonator structure known to the art of resonators may be used with the microchip laser. In fact, the use of the microchip laser makes such resonator 10 design easier, since the laser can be tuned to the cavity frequency.

If a nonlinear optical element is to be part of the resonant cavity, the boule of gain medium is sliced and lapped flat and parallel. The nonlinear optical material is 15 also lapped flat and parallel and bonded to the gain medium using transparent optical cement. The lengths of the gain material and the nonlinear optical material satisfy the relationship discussed above. After the gain medium and nonlinear optical material are bound, mirrors are applied to 20 the other surfaces either as multilayer dielectric coatings on the material itself or as separate mirrors, and the wafers are diced into chips.

It should be noted that one can construct a 25 microchip laser array or a microchip laser nonlinear frequency converter array by simply not dicing the wafers. That is, by leaving the microchip laser in wafer form, and associating the microchip laser wafer with a two dimensional diode laser array to pump the microchip laser array, a two dimensional array of microchip lasers is 30 immediately formed. Referring to Fig. 8.1, a two dimensional array of microchip lasers consists of an array

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of laser diodes 810 associated with a microchip laser wafer 812. Light from the laser diodes 814 excites the microchip laser to emit light. The two wafers can be cemented together using optically transparent cement. If the 5 microchip laser wafer also contains the nonlinear optical material within its resonant cavity, frequency conversion using a two wafer system is possible. If, however, the nonlinear optical material is not on the microchip laser, an array can still be constructed by simply placing the wafer 10 with the nonlinear optical material and Fabry-Perot resonant cavity 816 in association with the other wafers. Such a configuration is shown in Fig. 8.2. The resonant frequency of the nonlinear optical material cavity must be matched to the microchip frequency in the manner described above.

15 A microchip laser array is particularly useful if a directed laser beam is required. By properly modulating the phase of each microchip laser using, for example, individually addressable phase modulators placed in the output beam or within the cavity of each microchip laser, it 20 is possible to phase steer the array and thereby direct the beam. The output of the two-dimensional array of single-frequency microchip lasers may be coherently combined into a single beam using well known techniques of binary optics.

25 The diode-pumped microchip lasers according to the invention exhibit low pump threshold, high efficiency, and single frequency operation. These lasers can be continuously tuned across their gain-bandwidth in a single frequency using a transversely or longitudinally applied 30 stress to the microchip laser crystal. The microchip laser is applicable, for example, to frequency converters, modulators and Q-switches, with photolithographically

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deposited electrodes. It results in low costs, volume-producible lasers and electro-optic devices. The incorporation of nonlinear optical material, either inside or outside of the cavity, generates other wavelengths of 5 light. The output from such a device, in the visible or ultraviolet region, is useful for read and write optical disks and projection television applications.

What is claimed is:

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1. Solid state, optically pumped microchip laser comprising:

a solid state gain medium disposed between two mirrors, the distance between the mirrors selected so that  
5 the gain bandwidth of the gain medium is less than or substantially equal to the frequency separation of the cavity modes and such that one cavity mode frequency falls within the gain bandwidth of the medium; and

10 nonlinear optical material disposed to receive light from the gain medium, the nonlinear optical material selected to generate second or higher harmonics of the light from the gain medium, said nonlinear optical material contained within a Fabry-Perot resonator.

15 2. The microchip laser of claim 1 wherein said microchip laser further comprises an apparatus for applying a longitudinal stress to said gain medium to thereby tune a frequency of the light from the microchip laser to be coincident with a resonant frequency of the Fabry-Perot  
20 resonator containing a suitable nonlinear crystal.

25 3. The microchip laser of claim 1 wherein said microchip laser further comprises an apparatus for applying a transverse stress to said gain medium to thereby tune a frequency of the light from the microchip laser to be coincident with a resonant frequency of the Fabry-Perot resonator containing a suitable nonlinear crystal.

30 4. The microchip laser of claim 1 wherein said microchip laser further comprises an apparatus for changing the temperature of said gain medium to thereby tune a frequency of the light from the microchip laser to be

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coincident with a resonant frequency of the Fabry-Perot resonator containing a suitable nonlinear crystal.

5. The microchip laser of claim 1 wherein the  
5 nonlinear optical material is contained within a resonator  
with planar parallel faces.

6. The microchip laser of claim 1 wherein the  
nonlinear optical material is contained within a resonator  
10 having a flat face disposed toward the gain medium and a  
spherical face disposed away from the gain medium.

7. Solid state, optically pumped microchip laser  
comprising:

15 a solid state gain medium and nonlinear optical  
material combination disposed between two mirrors, the  
distance between the mirrors selected so that the gain  
bandwidth of the gain medium is less than or substantially  
equal to the frequency separation of the cavity modes and  
20 such that one cavity mode frequency falls within the gain  
bandwidth of the medium the nonlinear optical material  
selected to generate other frequencies from the light from  
the gain medium.

25 8. The microchip laser of claim 7 wherein the  
length of the gain medium and the length of the nonlinear  
material satisfies the relationship

$$\gamma_g \leq c/2(n_1 \ell_1 + n_2 \ell_2)$$

wherein  $n_1$  and  $\ell_1$  are the refractive index and length,  
30 respectively, of the gain medium,  $n_2$  and  $\ell_2$  are the  
refractive index and length, respectively, of the nonlinear

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optical materials and  $V_g$  is the bandwidth of the gain material.

9. The microchip laser of claim 1, 2, or 7 in  
5 which the gain medium is Nd:YAG.

10. The microchip laser of claim 9 in which the distance between the mirrors is about 730  $\mu$ m.

10 11. The microchip laser of claim 1, 2, or 7 in which the gain medium is Nd pentaphosphate.

12. The microchip laser of claim 11 in which the distance between the mirrors is about 100  $\mu$ m.

15 13. The microchip laser of claim 1, 2, or 7 in which the gain medium is Nd:GSGG.

20 14. The microchip laser of claim 13 in which the distance between the mirrors is about 625  $\mu$ m.

15. The microchip laser of claim 9 in which the optical pumping is tuned to 809  $\mu$ m.

25 16. The microchip laser of claim 1, 2, or 7 in which the mirrors are formed of multiple layers of dielectric.

30 17. The microchip laser of claims 1, 2, 7, 9, 11 or 13 in which the nonlinear material is  $MgO:LiNbO_3$ .

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18. The microchip laser of claims 1, 2, 7, 9, 11 or 13 in which the nonlinear material is KTP.

19. The microchip laser of claim 15 in which the 5 optical pumping source focuses onto the Nd:YAG crystal to a spot size of  $50 \mu\text{m}$ .

20. A method of making a microchip laser with a 10 nonlinear optical material laser light frequency converter comprising the steps of:

growing a boule of laser gain material;

slicing the boule of laser gain material into a wafer;

lapping the gain wafer flat and parallel and to a 15 thickness  $\ell$  wherein  $\ell$  satisfies the relationship

$\ell \leq c/2n\nu_g$  wherein  $n$  is the index of refraction for the gain materials and  $\nu_g$  is the bandwidth of the gain material;

20 applying mirrors to the gain material wafer so as to form a resonant cavity;

dicing the gain material with resonant cavity wafer into microchips;

associating the microchip with a pumping laser so as to allow the laser light to enter the gain material 25 through the face of the resonant cavity;

growing a boule of nonlinear optical material;

slicing the boule of nonlinear optical material into a wafer;

30 forming a Fabry-Perot resonant cavity upon said nonlinear optical material wafer;

dicing the nonlinear optical material wafer with Fabry-Perot resonant cavity into chips; and

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associating a nonlinear optical material chip with a microchip such that light emitted from the microchip upon stimulation by said pumping laser impinges upon the nonlinear optical material chip through a face of the  
5 Fabry-Perot resonant cavity.

21. A method of making a microchip laser with a nonlinear optical material laser light frequency converter comprising the steps of:

10 growing a boule of laser gain material;  
growing a boule of nonlinear optical material;  
slicing the boule of laser gain material into a wafer;  
slicing the boule of nonlinear optical material  
into a wafer;  
15 lapping the wafer of laser gain material and the  
wafer of nonlinear optical material parallel and flat to  
thicknesses  $\ell_1$  and  $\ell_2$  respectively, such that the  
thicknesses satisfy the relationship:

$$\gamma_g \leq c/(2n_1\ell_1 + n_2\ell_2)$$

20 wherein  $n_1$  is the refractive index of the gain medium,  $n_2$  is  
the refractive index of the nonlinear optical material and  
 $\gamma_g$  is the bandwidth of the gain medium;  
bonding the wafer of gain material to the wafer of  
nonlinear optical material using transparent optical cement;  
25 applying a mirror to each free face of the bonded  
wafers so as to form a resonant cavity;  
dicing the combined wafer and resonant cavity into  
microchips, and  
associating a microchip with resonant cavity with  
30 a pumping laser such that light from the pumping laser  
enters the resonant cavity through the face of the resonator  
associated with the gain medium.

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22. Solid state, optically pumped microchip laser comprising:

5 a solid state gain medium disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium substantially equal to the frequency separation of the cavity modes and such that one cavity mode frequency falls within the gain bandwidth of  
10 the medium.

23. The laser of claim 22 further comprising an apparatus adapted to change the temperature of said gain medium to thereby thermally tune said laser.

24. The laser of claim 22 further comprising an  
15 apparatus adapted to apply a longitudinal stress to said gain medium to thereby stress tune said laser.

25. The laser of claim 22 further comprising an apparatus adapted to apply a transverse stress to said gain medium to thereby stress tune said laser.

20 26. An array of microchip lasers comprised of a wafer of gain material disposed between two mirrors, the thickness of the wafer selected so that the gain bandwidth of the gain medium is less than or substantially equal to the frequency separation of the cavity modes and such that  
25 one cavity mode frequency falls within the gain bandwidth of the medium; and positioned adjacent to a wafer of diode lasers aligned so as to stimulate said gain medium into light emission.

30

27. The array of claim 26 further comprising a wafer of nonlinear optical material disposed between two

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mirrors positioned so as to form a Fabry-Perot resonator with a resonant frequency coincident with the mode of oscillation of the microlasers and positioned so as to be irradiated by said microlasers and thereby stimulated into 5 optical frequency conversion.

28. Solid state, optically pumped microchip laser comprising:

10 a solid state gain medium disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium less than the frequency separation of the cavity modes and such that one cavity mode frequency falls within the gain bandwidth of the medium; and

15 an apparatus adapted for changing the temperature of said gain medium and thereby thermally tuning said laser.

29. Solid state, optically pumped microchip laser comprising:

20 a solid state gain medium disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium less than the frequency separation of the cavity modes and such that one cavity mode frequency falls within the gain bandwidth of the medium; and

25 an apparatus adapted for applying a longitudinal stress to said gain medium and thereby stress tuning said laser.

30 30. Solid state, optically pumped microchip laser comprising:

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a solid state gain medium disposed between two mirrors, the distance between the mirrors selected so that the gain bandwidth of the gain medium less than the frequency separation of the cavity modes and such that one cavity mode frequency falls within the gain bandwidth of the medium; and

an apparatus adapted for applying a transverse stress to said gain medium and thereby stress tuning said laser.

10

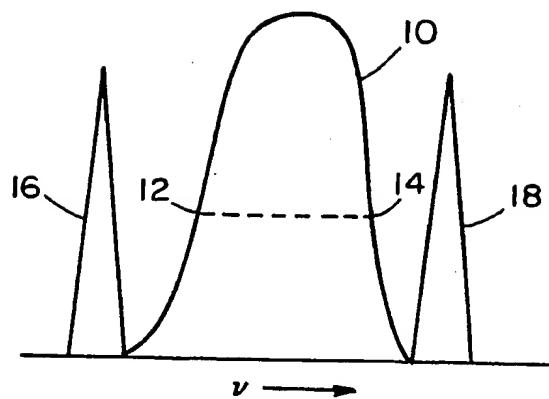


FIG. 1.1

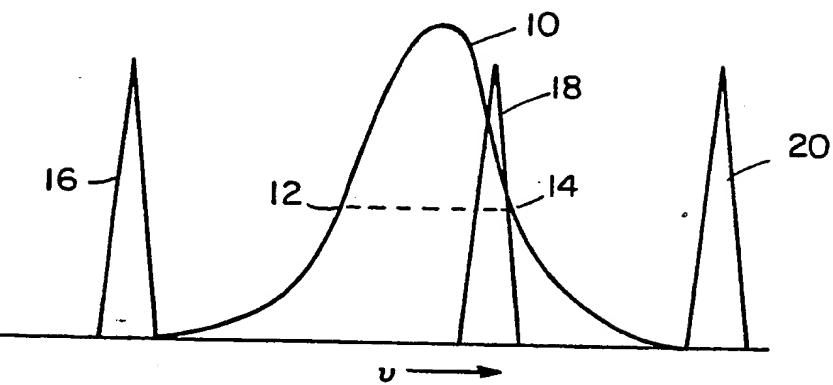


FIG. 1.2

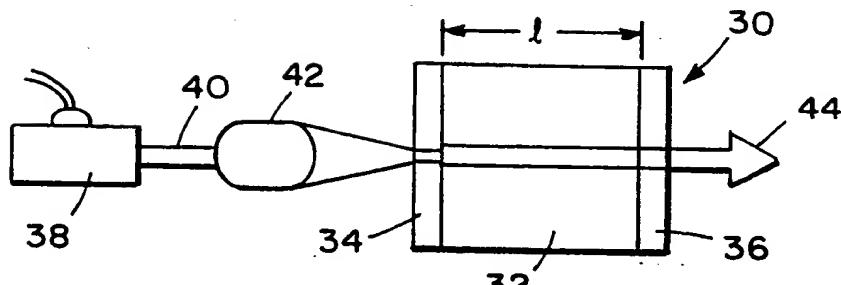


FIG. 2.1

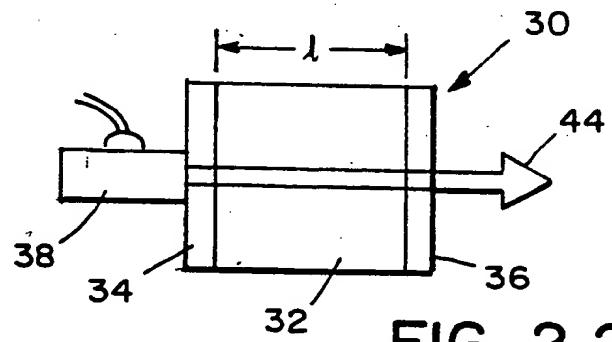


FIG. 2.2

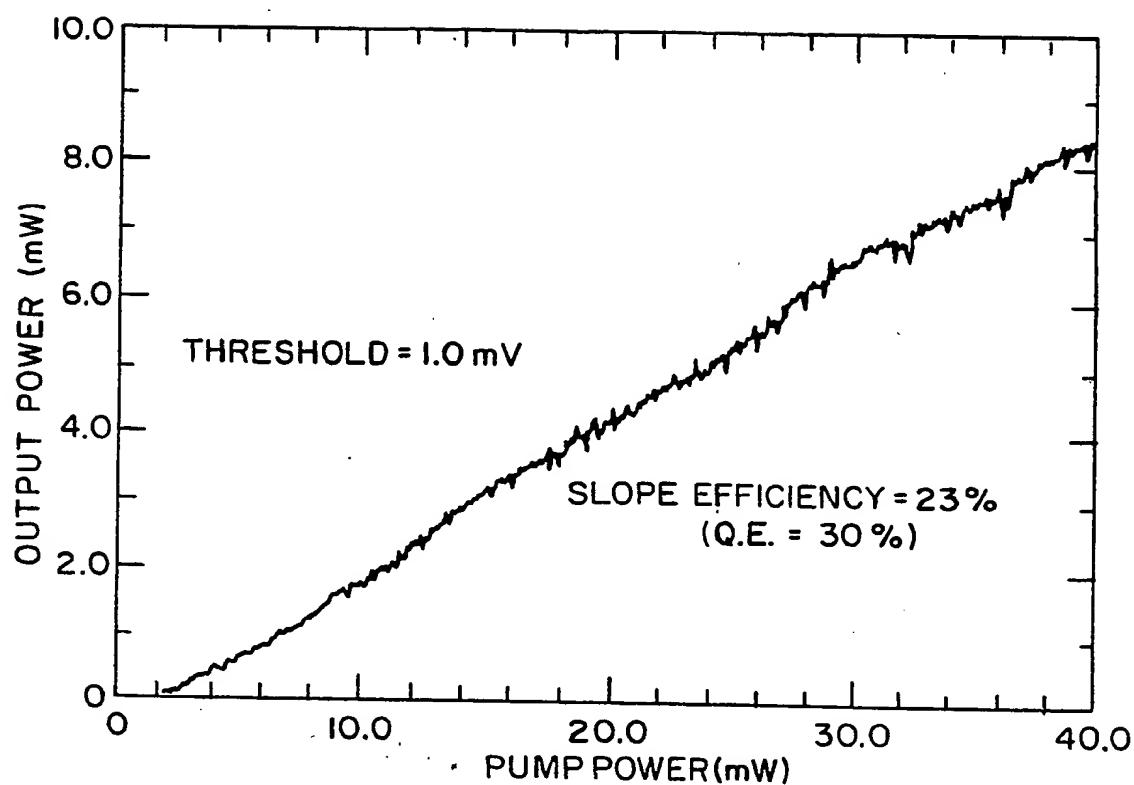


FIG. 4

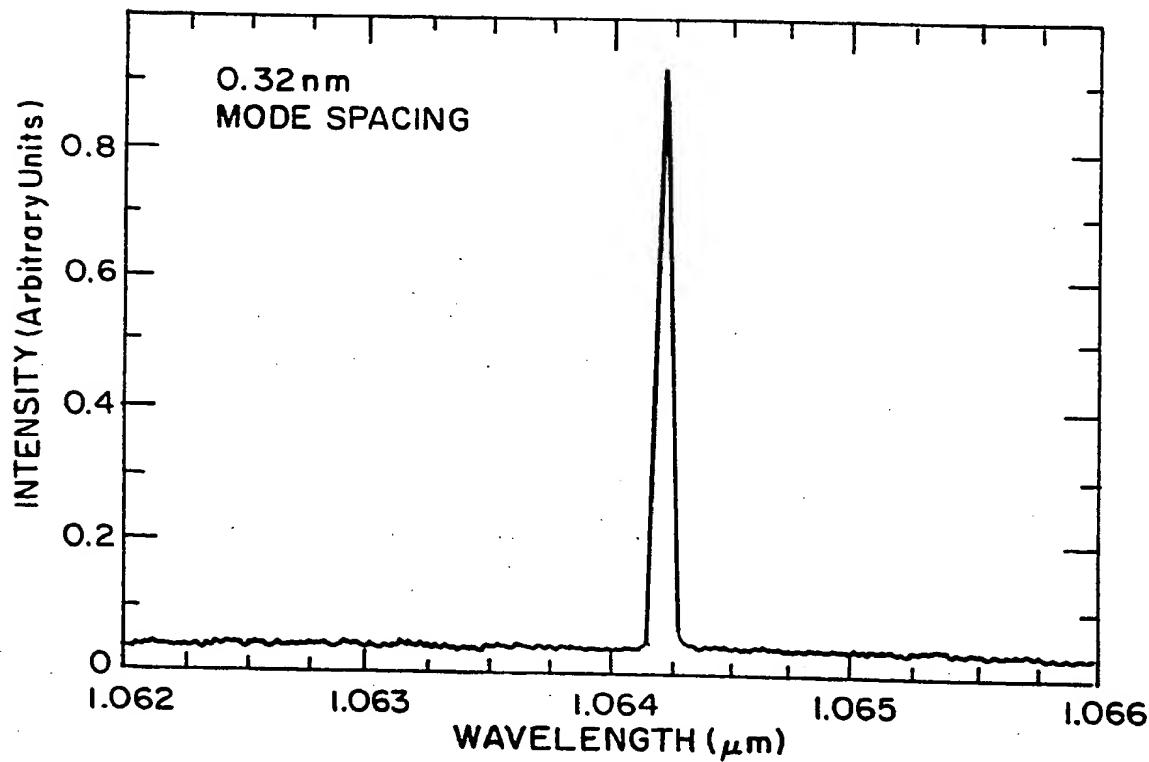


FIG. 3

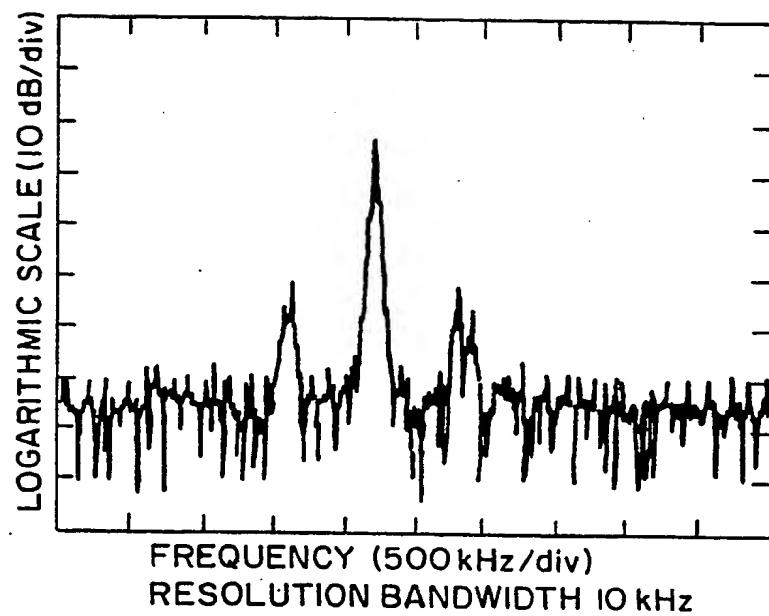


FIG. 5.1

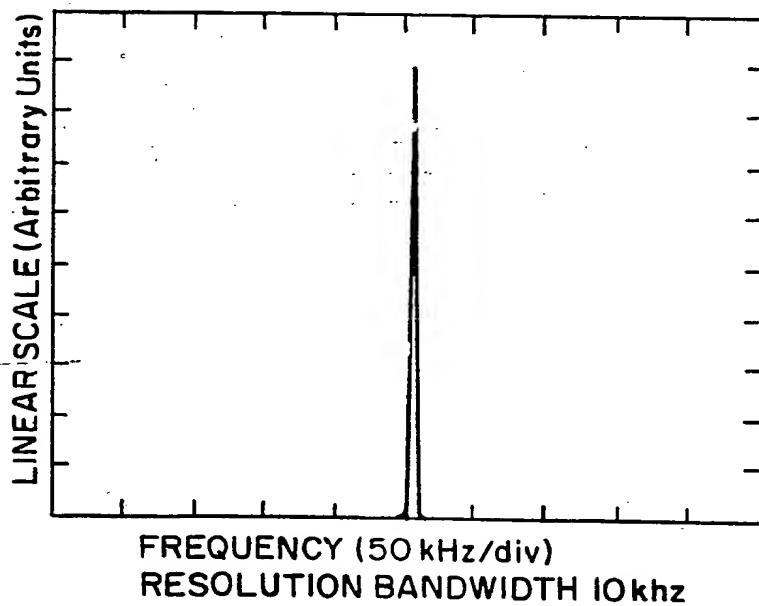


FIG. 5.2

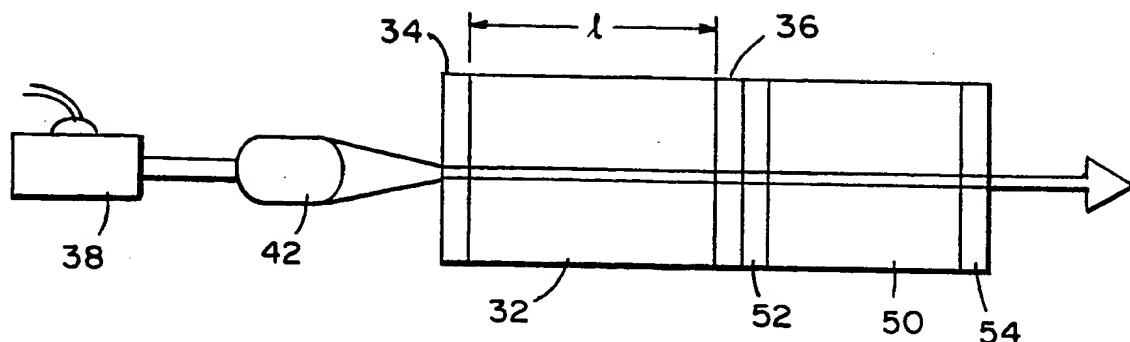


FIG. 6.1

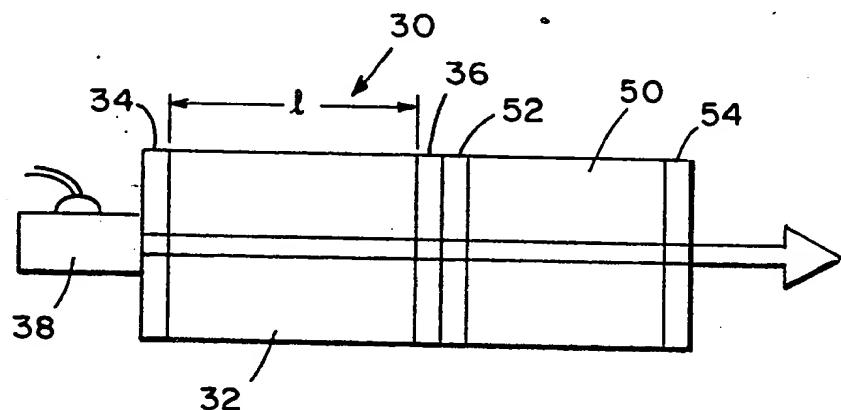


FIG. 6.2

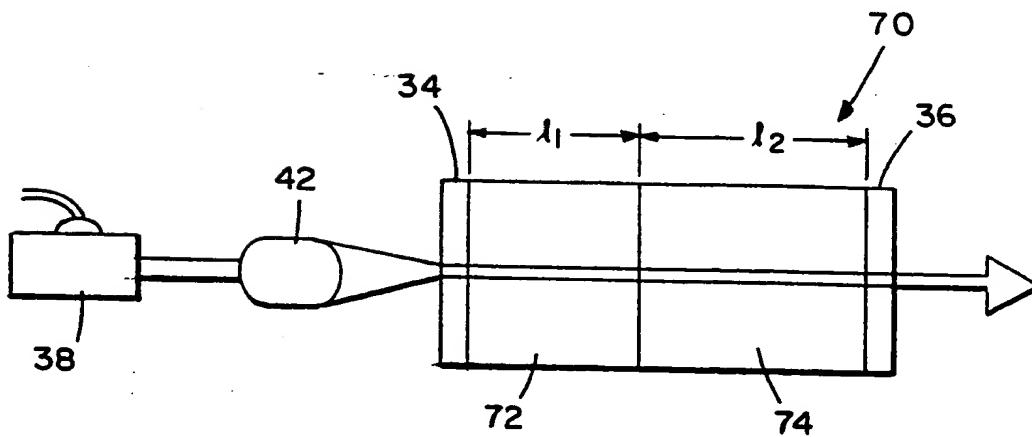


FIG. 7

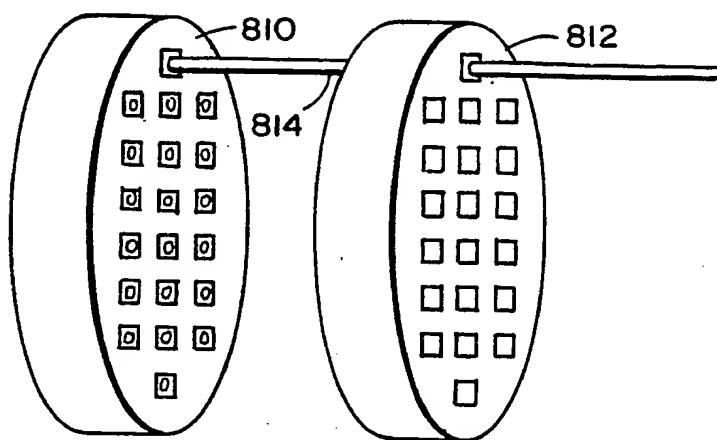


FIG. 8.1

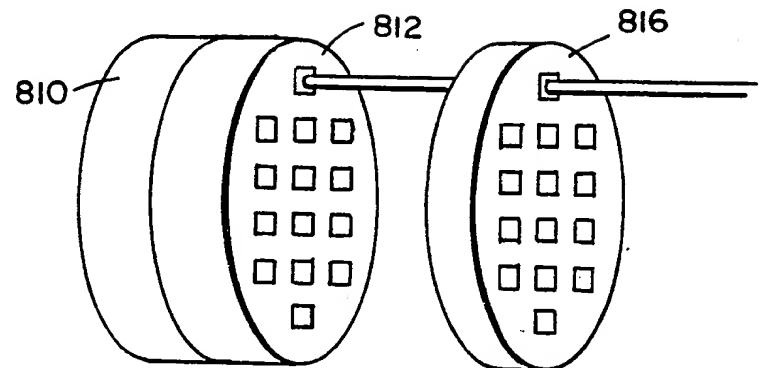


FIG. 8.2

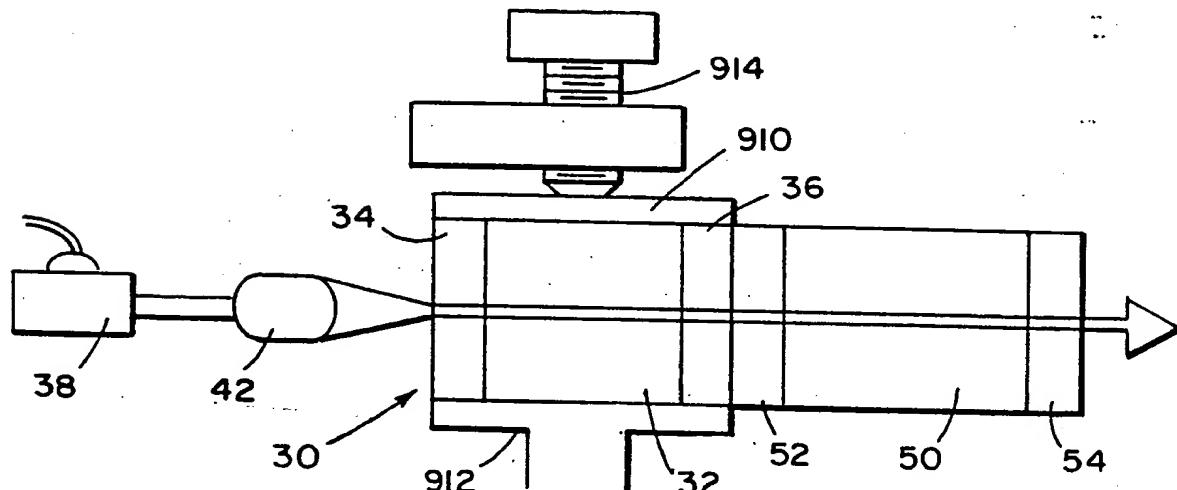


FIG. 9.1

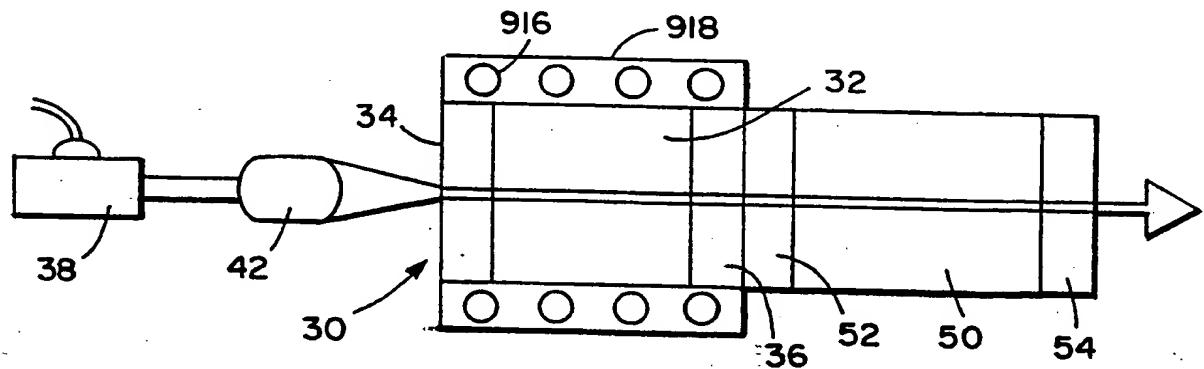


FIG. 9.2

# INTERNATIONAL SEARCH REPORT

International Application No. PCT/US90/00644

## I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) <sup>6</sup>

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC<sup>5</sup> H01S 3/05  
U.S. CL. 372/21

## II. FIELDS SEARCHED

Classification System	Minimum Documentation Searched <sup>7</sup>
	Classification Symbols
U.S. CL.	372/19, 20, 21, 32, 39, 41, 50, 75, 92 330/4.3, 437/129

Documentation Searched other than Minimum Documentation  
to the Extent that such Documents are Included in the Fields Searched <sup>8</sup>

## III. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>9</sup>

Category <sup>10</sup>	Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>13</sup>
A	US, A 4,002,725 Bridenbaugh et al 11 January 1977	
A	US, A 4,734,912 Scerbak et al 29 March 1988	
A	US, A 4,739,507 Byer et al 19 April 1988	
A	US, A 4,797,893 Dixon 10 JANUARY 1989	
A	Digest of Technical papers, topical meeting on Integrated Optics, January 21-24, 1974 New Orleans, Louisiana, D. Castleberry, "A single mode 2.06 mm miniature Laser", MB7,pp1-4	
A	Review of The Electrical Communication Laboratories, Vol. 26, Nos. 9-10, September-October, 1978 M. Saruwatari et al " Electroluminescent Diode Pumped Miniaturized LiNdP4O12 Lasers", pp. 1111-1128.	
A	Optics letters, Vol. 12 No. 12, December 1987. A. Owyong et al, "stress-induced tuning of a diode-laser-excited monolithic Nd:YAG laser-", pp 999-1001.	

\* Special categories of cited documents: <sup>10</sup>

"A" document defining the general state of the art which is not considered to be of particular relevance  
"E" earlier document but published on or after the international filing date  
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)  
"O" document referring to an oral disclosure, use, exhibition or other means  
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

## IV. CERTIFICATION

Date of the Actual Completion of the International Search

16 MAY 1990

Date of Mailing of this International Search Report

06 JUL 1990

International Searching Authority

ISA/US

Signature of Authorized Officer

JAMES W. DAVIE-SDJ-5-30-90